

# (12) UK Patent Application (19) GB (11) 2 346 452 (13) A

(43) Date of A Publication 09.08.2000

(21) Application No 9902479.6

(22) Date of Filing 05.02.1999

(71) Applicant(s)

The University Court of the University of Glasgow  
(Incorporated in the United Kingdom)  
University Avenue, Glasgow, G12 8QQ,  
United Kingdom

(72) Inventor(s)

Paulo Vicente da Silva Marques  
James Ronald Bonar  
James Stewart Aitchison

(74) Agent and/or Address for Service

Murgitroyd & Company  
373 Scotland Street, GLASGOW, G5 8QA,  
United Kingdom

(51) INT CL<sup>7</sup>

G02B 6/16

(52) UK CL (Edition R )

G2J JGDA

(56) Documents Cited

EP 0803589 A EP 0617301 A EP 0607884 A  
US 4871221 A

(58) Field of Search

UK CL (Edition Q ) G2J JGDA  
INT CL<sup>6</sup> G02B

(54) Abstract Title

Waveguides

(57) A waveguide for an optical circuit comprises a substrate 6; a buffer layer 7 formed on the substrate; a doped lower cladding layer 8 formed on the buffer layer; a doped waveguide core 13 formed on the lower cladding layer; and a doped upper cladding layer 12 embedding the waveguide core. The waveguide core includes mobile dopant ions, such which as P or F have diffused into the upper cladding layer and the lower cladding layer to form an ion diffusion region around said waveguide core such that the waveguide core boundary walls are substantially smooth. Methods of fabricating the waveguide are also described. Cladding layers 8 and 13 are preferably doped with P or B ions.

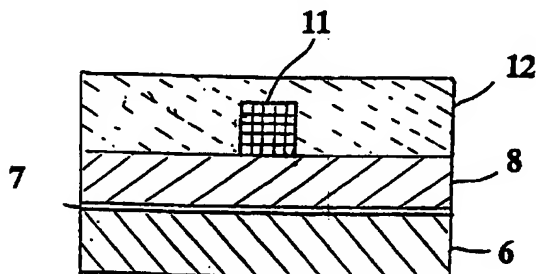


FIG. 2C

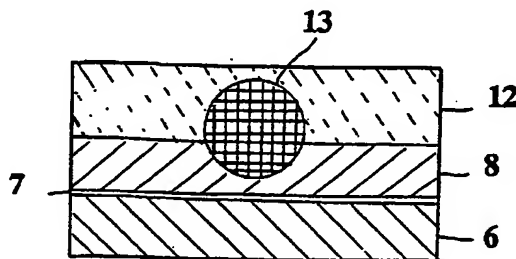


FIG. 2E

GB 2 346 452 A

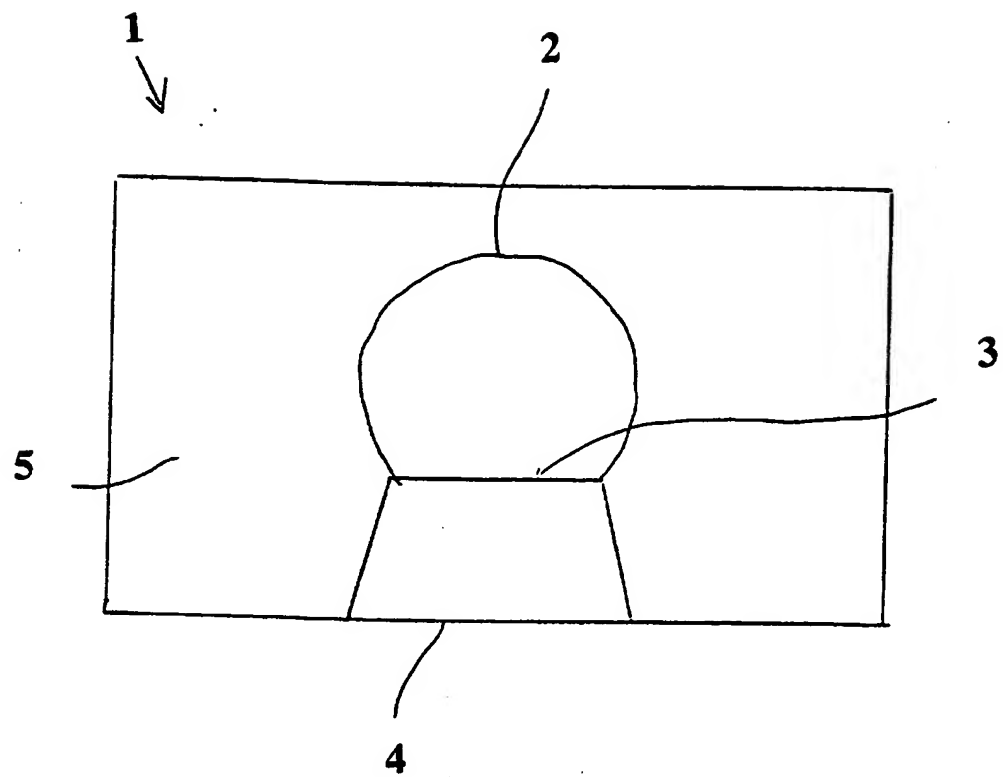


FIG. 1

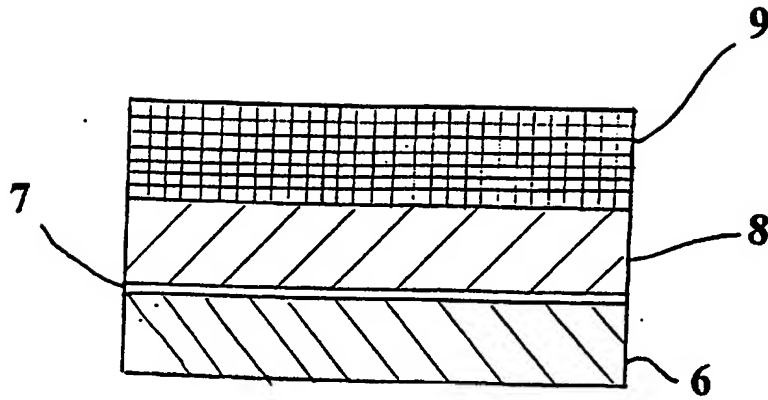


FIG. 2A

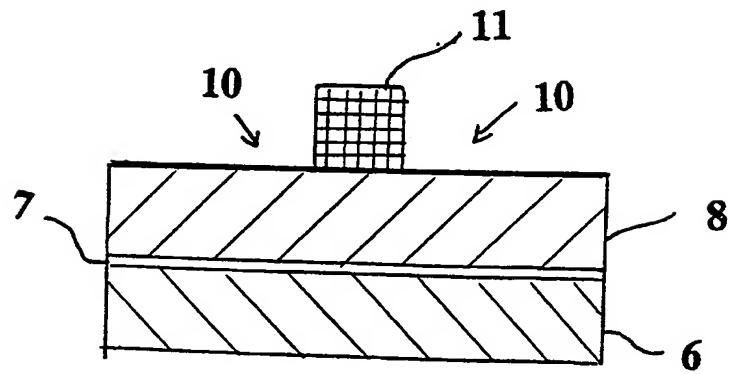


FIG. 2B

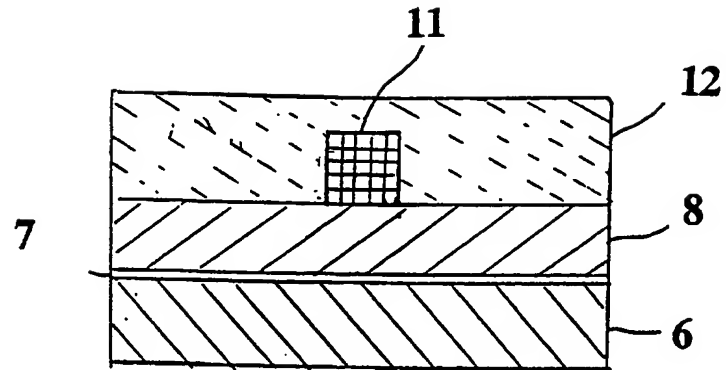


FIG. 2C

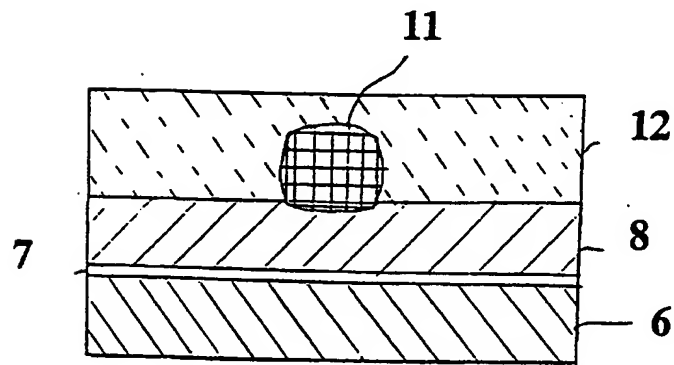


FIG. 2D

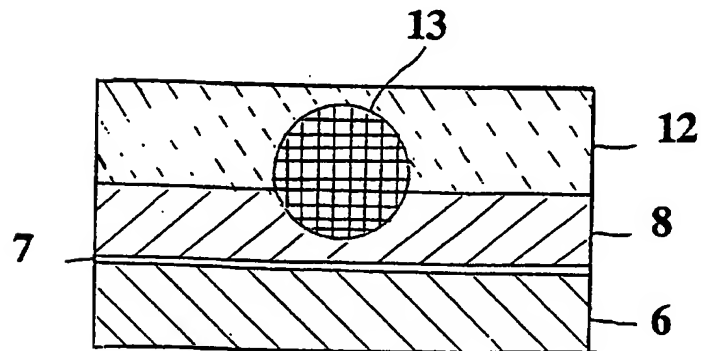


FIG. 2E

1  
2  
3  
4  
5  
6  
7  
8  
9

10 WAVEGUIDE FOR AN OPTICAL CIRCUIT AND METHOD OF  
11 FABRICATION THEREOF

12

13 FIELD OF THE INVENTION

14

15 The present invention relates to a waveguide for an  
16 optical circuit, and a method of fabrication thereof.

17

18 The method relates in particular to the fabrication of  
19 a waveguide for an optical circuit with smoothed  
20 waveguide core boundaries. More specifically, the  
21 method relates to the fabrication of a rounded,  
22 elliptical or circular waveguide core by the isotropic  
23 diffusion of dopants in a core layer of a  
24 phosphosilicate waveguide wafer, such that the diffused  
25 core layer forms the circular waveguide core. This  
26 diffusion is thermally promoted either during the  
27 deposition of an upper cladding layer or by subsequent  
28 thermal processing of the waveguide wafer.

29

30 BACKGROUND OF THE INVENTION

31

32 The general process of fabricating a glass waveguide  
33 for optical circuits comprises forming at least one  
34 buffer layer, e.g. a thermal oxide layer, on a silicon  
35 wafer substrate. Additional buffer layers and/or at

1 least one lower cladding layers may then be formed on  
2 top of the buffer layer. A core layer composed of a  
3 doped silica film is then formed on top of the buffer  
4 layer or lower cladding layer.

5  
6 The core layer is then etched, for example, by reactive  
7 ion techniques, to form a square or rectangular  
8 waveguide or other suitable cross-sectional profile.  
9 The etched core is then embedded by an upper cladding  
10 layer.

11 The core layer refractive index is usually higher than  
12 that of the surrounding layers. This concentrates the  
13 propagation of light in the core layer.

14  
15 Planar channel waveguides are usually formed using dry  
16 etch methods to produce waveguides with square or  
17 rectangular cross-sections. Such angular waveguides  
18 have several disadvantages, in particular the  
19 geometrical mismatch between the waveguides and optical  
20 fibres in an optical circuit. The production of channel  
21 waveguides with a circular cross-section is  
22 particularly advantageous in that this increases the  
23 transmission efficiency between the waveguide and the  
24 rest of an optical circuit.

25  
26 Channel waveguides are also susceptible to scatter loss  
27 (Mie scattering) due to imperfections in their  
28 sidewalls. This is reduced by smoothing the profile of  
29 the waveguide and this provides low propagation loss in  
30 the waveguides.

31  
32 Circular optical waveguides are known in principle (for  
33 example, see Sun et al., "Silica-based circular cross-  
34 sectioned channel waveguides", IEEE Photonics  
35 Technology Letters, 3, p.p. 238-240, 1991). Sun et  
36 al., disclose large dimension ( $\sim 50\mu\text{m}$ )  $\text{GeO}_2$  doped silica

1 waveguides which are reactive ion etched to form  
2 rectangular channel cross-sections. This method  
3 involves depositing a lower cladding layer with a  
4 reduced amount of Germanium doped silicon on to the  
5 wafer substrate prior to the deposition of a core  
6 layer. When the wafer is placed in the selective wet  
7 etch, the lower cladding layer is etched at a much  
8 faster rate to form a pedestal underneath the core  
9 region.

10

11 According to Sun et al., the waveguide can then be  
12 heated above the core softening temperature so that the  
13 surface tension of the glass functions to round the  
14 waveguide core. Such wet etching techniques are time  
15 consuming and moreover, do not offer truly circular  
16 cross sections as the core cannot be rounded at the  
17 interface between the core layer and the pedestal  
18 (i.e., the lower cladding layer lying directly beneath  
19 the core).

20

21 The current invention in contrast relies on the  
22 mobility of dopant ions in a square or rectangular  
23 etched core to migrate outwards into both upper and  
24 lower cladding layers. This forms waveguides which  
25 have substantially smoothed boundary walls, in  
26 particular the side walls are smoothed.

27

28 Further diffusion rounds the core region, and providing  
29 the diffusion is sufficiently isotropic the core region  
30 becomes sufficiently rounded to form a circular  
31 waveguide. This diffusion is thermally promoted either  
32 during the consolidation of the upper cladding layer or  
33 during subsequent thermal processing. By selecting the  
34 composition of the upper and lower cladding layers, the  
35 refractive indexes and consolidation temperatures can  
36 be chosen to modify the rate at which the core dopant

1 ions diffuse into each layer and the ellipticity of the  
2 resulting waveguide core accordingly adjusted.

3

4

5 SUMMARY OF THE INVENTION

6

7 According to a first aspect of the present invention,  
8 there is provided a waveguide for an optical circuit  
9 comprising:

10 a substrate;

11 a doped lower cladding layer;

12 a doped waveguide core formed on the lower  
13 cladding layer; and

14 a doped upper cladding layer embedding the  
15 waveguide core;

16 wherein the waveguide core includes mobile dopant  
17 ions which have diffused into the upper cladding layer  
18 and the lower cladding layer to form an ion diffusion  
19 region around said waveguide core such that the  
20 waveguide core boundary walls are substantially smooth.

21

22 According to a second aspect of the present invention,  
23 there is provided a method for fabricating a waveguide  
24 comprising the steps of:

25 providing a substrate;

26 forming a doped lower cladding layer;

27 forming a doped core layer on the lower cladding  
28 layer;

29 forming a waveguide core from the core layer;

30 forming a doped upper cladding layer to embed the  
31 waveguide core;

32 wherein mobile ion dopants included in the core  
33 layer undergo diffusion into the surrounding upper  
34 cladding layer and lower cladding layer to form an ion  
35 diffusion region around the waveguide core such that  
36 the waveguide core boundary walls are substantially



1 smooth.

2

3 DESCRIPTION OF THE DRAWINGS

4

5 Embodiments of the present invention will now be  
6 described by way of example only with reference to the  
7 accompanying drawings in which:-

8

9 Fig. 1 is a cross-sectional diagram of a conventionally  
10 rounded waveguide;

11

12 Figs. 2A to 2E are a cross-sectional diagrams showing  
13 stages in the fabrication of a rounded waveguide  
14 according to the present invention;

15

16 DETAILED DESCRIPTION OF THE INVENTION

17

18 With reference to the drawings, there is described now  
19 a waveguide for an optical circuit and a method of  
20 fabrication thereof according to the present invention.

21

22 A waveguide produced by conventional techniques which  
23 can partially round the cross-section of the core layer  
24 of a waveguide is shown in Fig.1. This illustrates such  
25 a waveguide 1 with a rounded core upper cross-section 2  
26 and flat base 3 supported by a pedestal 4 embedded in a  
27 cladding layer 5 as might be formed by the conventional  
28 method of *Sun et al.*

29

30 The present invention provides a waveguide which does  
31 not exhibit the flat base 3 shown in Fig.1. Various  
32 stages in the method of fabricating such a waveguide  
33 will now be described with reference to Figs. 2A to 2E.

34

35 Fig. 2A is a schematic diagram showing the preliminary  
36 stages in a method of fabricating a waveguide with an

1 elliptical or rounded cross-section from a silicon  
2 wafer according to a first embodiment of the invention.

3  
4 In this embodiment, a silicon substrate 6 is covered  
5 with a buffer layer 7 comprising thermally oxidised  
6 silicon. In alternative embodiments of the invention,  
7 the substrate 6 comprises silica and sapphire and the  
8 buffer layer 7 further includes at least one Phosphorus  
9 oxide and/or Boron oxide. The thickness of the  
10 thermally oxidised silicon buffer layer 7 ranges  
11 between 0.2  $\mu\text{m}$  and 20  $\mu\text{m}$ .

12  
13 A lower cladding layer 8, doped with Phosphorus and  
14 Boron ions and having a refractive index matched to the  
15 buffer layer 7, is then deposited using a Flame  
16 Hydrolysis Deposition (FHD) process on to the buffer  
17 layer 7, and is consolidated either in an electrical  
18 furnace or by using an FHD burner.

19  
20 By way of example, the FHD process used for deposition  
21 of the lower cladding layer 8 can employ the following  
22 input feed flow rates for the feed gases:-  
23 Shroud gas 5 litres/min;  $\text{O}_2$  4 litres/min;  
24  $\text{H}_2$  2 litres/min;  $\text{SiCl}_4$  carrier gas 0.15 litres/min;  
25  $\text{PCl}_3$  carrier gas 0.04 litres/min;  
26  $\text{BCl}_3$  carrier gas 0.09 litres/min. The halides are  
27 carried, for example, by an  $\text{N}_2$  carrier gas, and the  
28 shroud gas can, for example, be  $\text{N}_2$ .

29  
30 The lower cladding layer 8 formed comprises silica,  
31 Phosphorus oxide, and Boron oxide; for example  $\text{SiO}_2\text{-P}_2\text{O}_5\text{-}$   
32  $\text{B}_2\text{O}_3$ . In alternative embodiments, the lower cladding  
33 layer 8 may contain dopant ions in addition to  $\text{SiO}_2\text{-P}_2\text{O}_5\text{-}$   
34  $\text{B}_2\text{O}_3$ . The doping levels for the silica, Phosphorus oxide  
35 and Boron oxide in the lower cladding layer 8 are 82  
36 wt% silica, 5 wt% Phosphorus oxide and 13 wt% Boron

1 oxide. Varying the flow rates of the input gases in  
2 the FHD burner results in different doping levels. In  
3 other embodiments of the invention, the preferred  
4 doping levels range between 75 to 95 wt% silica, 1 to 7  
5 wt% Phosphorus oxide and 4 to 18 wt% Boron oxide, or  
6 alternatively range between 80 to 90 wt% silica, 2.5 to  
7 6 wt% Phosphorus oxide, and 7.5 to 14 wt% Boron oxide.  
8

9 The lower cladding layer 8 is consolidated by fully  
10 fusing the layer in an electric furnace at a  
11 temperature of 1250°C, which is in a preferred range of  
12 temperatures of between 1100°C to 1350°C.  
13

14 In alternative embodiments, the lower cladding layer 8  
15 is deposited using an FHD process and can be  
16 consolidated at different temperatures within a range  
17 of temperatures of between 950°C to 1400°C.  
18

19 In a further alternative, the lower cladding layer 8 is  
20 deposited by a Flame Hydrolysis Deposition (FHD)  
21 process and partially consolidated at this stage and  
22 fully consolidated subsequently.  
23

24 The thickness of the lower cladding layer 8 deposited  
25 is 2  $\mu\text{m}$  but can range between 1  $\mu\text{m}$  and 20  $\mu\text{m}$ .  
26

27 In alternative embodiments, where no buffer layer is  
28 employed, the lower cladding layer 8 can be formed  
29 directly on top of the substrate 6.  
30

31 A core layer 9 comprising Phosphorus oxide and silica,  
32 for example,  $\text{P}_2\text{O}_5\text{-SiO}_2$ , is then formed on the lower  
33 cladding layer 8. The refractive index of the core  
34 layer 9 differs from that of the lower cladding layer 8  
35 by 0.75%, and may differ by a value within the range of  
36 0.05 % to 2 %.

1 By way of example, the FHD process used for deposition  
2 of the core layer 9 can employ the following input feed  
3 flow rates for the feed gases:-  
4 Shroud gas 5 litres/min; O<sub>2</sub> 6 litres/min;  
5 H<sub>2</sub> 4 litres/min; SiCl<sub>4</sub> carrier gas 0.15 litres/min;  
6 PCl<sub>3</sub> carrier gas 0.018 litres/min. The halides are  
7 carried, for example, by an N<sub>2</sub> carrier gas, and the  
8 shroud gas can, for example, be N<sub>2</sub>.

9  
10 The core layer 9 is consolidated by fully fusing the  
11 layer in an electric furnace at a temperature of  
12 1200°C, which is in a preferred range of temperatures  
13 of between 1100°C to 1385°C.

14  
15 In alternative embodiments, the core layer 9 is  
16 deposited using an FHD process and can be consolidated  
17 at different temperatures within a range of  
18 temperatures of between 950°C to 1400°C.

19  
20 In a further alternative, the core layer 9 is partially  
21 consolidated at this stage and consolidated  
22 subsequently.

23  
24 The dopant levels for the core layer 9 are 80 wt%  
25 silica and 20 wt% Phosphorus oxide in the preferred  
26 embodiment. In alternative embodiments, the input  
27 gases into the FHD burner are varied to give core  
28 dopant levels between 75 to 95 wt% silica and 5 to 25  
29 wt% Phosphorus oxide respectively. The thickness of  
30 the core layer deposited is 6 µm but can range between  
31 2 µm and 60 µm.

32  
33 The core layer mobile ion dopants include Phosphorus  
34 ions but could, for example, include Fluorine ions. In  
35 alternative embodiments, the core layer 9 is doped  
36 Phosphorus and co-doped with ions with desired

1 properties to effect reduction of the sintering  
2 temperature and/or to effect increase of the core layer  
3 refractive index. The co-dopants may be selected from  
4 the group comprising Aluminium, Boron, Germanium, Tin  
5 and/or Titanium. For example, co-doping with Germanium  
6 reduces the sintering temperature and raises the silica  
7 based core layer 9 refractive index so that the  
8 refractive index is higher than the refractive index of  
9 the lower cladding layer 8 on top of which the core  
10 layer 9 is deposited.

11

12 The lower cladding layer 8 is susceptible to  
13 interdiffusion from the dopant ions from the core layer  
14 9. In contrast, the buffer layer 7 acts as a barrier  
15 against interdiffusion.

16

17 Fig. 2B shows the subsequent stage in the method of  
18 fabricating an optical waveguide in which the core  
19 layer 9 is redefined by removing regions 10 by a  
20 reactive ion etching (RIE) technique to form a square  
21 waveguide core 11. In general, a square or rectangular  
22 waveguide core 11 whose dimensions range from 2  $\mu\text{m}$  to  
23 60  $\mu\text{m}$  will be suitable in the method of fabricating an  
24 optical waveguide, preferred dimensions being such as  
25 to give a waveguide core 11 of 6  $\mu\text{m}$  x 6  $\mu\text{m}$ .

26

27 Alternative techniques for forming a square or  
28 rectangular waveguide core 11 can be used, or a  
29 combination of techniques. For example, dry etching  
30 techniques (e.g. reactive ion etching, ion milling,  
31 and/or plasma etching processes), a photolithographic  
32 technique, and/or a mechanical sawing process may be  
33 used.

34

35 Subsequently, the waveguide core 11 is embedded by an  
36 upper cladding layer 12 (as shown in Fig. 2C)

1 comprising Phosphorus oxide, Boron oxide and silica.  
2 Preferably, the upper cladding layer 12 has the same  
3 composition as the lower cladding layer 8 ( $P_2O_5$ - $B_2O_3$ -  
4  $SiO_2$ ) and the same refractive index. Alternatively, the  
5 upper cladding layer 12 can have a different  
6 composition from the lower cladding layer 8 but can  
7 have substantially the same refractive index. The  
8 upper cladding layer 12 can be deposited using the same  
9 input gas flow parameters into the FHD apparatus as for  
10 the lower cladding layer 8.

11  
12 The upper cladding layer 12 is then consolidated in a  
13 furnace and by adjusting the duration and temperature  
14 of the heat treatment the amount of diffusion of the  
15 dopant ions in the waveguide core 11 can be adjusted.

16  
17 The upper cladding layer 12 is consolidated by fully  
18 fusing the upper cladding layer 12 in an electric  
19 furnace for about 90 minutes at a minimum temperature  
20 of 1050°C and preferably at a temperature of 1200°C,  
21 which is in a preferred range of temperatures of  
22 between 1100°C to 1250°C.

23  
24 The consolidation temperature of the upper cladding  
25 layer 12 is a minimum of 1050 °C for the given co-  
26 dopant levels. In alternative embodiments, for other  
27 co-dopant levels, the upper cladding layer 12 is  
28 deposited using an FHD process and can be consolidated  
29 at different temperatures within a range of  
30 temperatures of between 950°C to 1250°C. By suitably  
31 varying the co-dopant levels in the upper cladding  
32 layer 12 the consolidation temperature can be reduced  
33 to below 950°C.

34  
35 Fig. 2D shows how the consolidation temperature of the  
36 upper cladding layer 12 promotes diffusion of the

1 mobile core dopant ions into the upper cladding layer  
2 12 and lower cladding layer 8. The composition of the  
3 upper and lower cladding layers 8 and 12 gives a  
4 diffusion length of  $2\mu\text{m}$  when the consolidation  
5 temperature of the core layer 9 and upper cladding  
6 layer 12 is  $1200^{\circ}\text{C}$ . More typically, the diffusion  
7 length is between the range of  $0.1\mu\text{m}$  to  $3\mu\text{m}$  for the  
8 preferred ranges of consolidation temperatures.  
9

10 The upper cladding layer 12 is consolidated at a  
11 temperature which is the same as or greater than a  
12 temperature which promotes efficient diffusion of the  
13 waveguide core 11.  
14

15 The ion dopant concentration in the lower cladding  
16 layer 8 and upper cladding layer 12 is chosen so that  
17 the waveguide core 11 has a higher concentration of  
18 dopant ions to promote diffusion of the waveguide core  
19 11 dopant ions into the lower cladding layer 8 and  
20 upper cladding layer 12. In the preferred embodiment,  
21 the diffusion of the mobile ion dopants in the  
22 waveguide core 11 into the surrounding cladding layers  
23 8 and 12 occurs during consolidation of the upper  
24 cladding layer 12, during which the core boundaries of  
25 the waveguide core 11 are rounded and a waveguide 13 is  
26 formed which is circular in cross-section.  
27

28 In an alternative embodiment, subsequent thermal  
29 processing after the consolidation of the upper  
30 cladding layer 12 promotes diffusion of the mobile ion  
31 dopants in the waveguide core 11 into the surrounding  
32 cladding layers 8 and 12.  
33

34 Fig. 2E shows the resulting rounded waveguide 13.  
35

36 In other embodiments of the invention, a silica based

1 waveguide core 11 may be doped with Phosphorus and  
2 Germanium to raise the refractive index of the  
3 waveguide core 11 and to reduce the consolidation  
4 temperature of the waveguide core 11. Alternative  
5 techniques may be used to redefine the waveguide core  
6 11 from the core layer 9; e.g. photolithographic,  
7 plasma etching processes, ion milling process,  
8 mechanical sawing process, and RIE processes.

9  
10 In other embodiments, the waveguide core 11 may  
11 comprise more than one core layer 9. Such core layers  
12 9 could be chosen to have substantially the same  
13 refractive index but differ in material composition.

14  
15 Other embodiments of the invention may require  
16 additional interdiffusion upper cladding layers 12 and  
17 lower cladding layers 8 to be deposited above and/or  
18 below the waveguide core 11. To promote isotropic  
19 diffusion, the lower cladding layers 8 may have the  
20 same composition and/or the same refractive index as  
21 that of the upper cladding layers 12. The isotropy of  
22 the refractive index surrounding the waveguide core 11  
23 promotes circular diffusion and a circular waveguide  
24 core 13 results.

25  
26 In other embodiments, a Chemical Vapour Deposition  
27 (CVD) method, or a Plasma Enhanced Chemical Vapour  
28 Deposition (PECVD) method, or a combination of these  
29 methods can be used to form the cladding layers 8 and  
30 12 and the core layer 9. Subsequent thermal processing  
31 of the waveguide promotes diffusion of ion dopants from  
32 the waveguide core 11 into the surrounding upper  
33 cladding and lower cladding layers 8 and 12.

34  
35 In other embodiments, the lower cladding layer 8 may be  
36 only partially consolidated before the core layer 9 is



1 deposited thereon and fully consolidated when the core  
2 layer 9 is consolidated. Furthermore, the waveguide  
3 core 11 may only be partially consolidated when the  
4 upper cladding layer 12 is formed thereon and may be  
5 fully consolidated when the upper cladding layer 12 is  
6 consolidated. Also, the FHD burner can be used for  
7 fusing by passing the burner over the waveguide to fuse  
8 the lower cladding and upper cladding layers 8 and 12  
9 and to fuse the core layer 9.

10

11 While several embodiments of the present invention have  
12 been described and illustrated, it will be apparent to  
13 those skilled in the art once given this disclosure  
14 that various modifications, changes, improvements and  
15 variations may be made without departing from the  
16 spirit or scope of this invention.

## 1     Claims:

2

3     1     A waveguide for an optical circuit comprising:

4           a substrate;

5           a doped lower cladding layer;

6           a doped waveguide core formed on the lower

7 cladding layer; and

8           a doped upper cladding layer embedding the

9 waveguide core;

10           wherein the waveguide core includes mobile dopant  
11 ions which have diffused into the upper cladding layer  
12 and the lower cladding layer to form an ion diffusion  
13 region around said waveguide core such that the  
14 waveguide core boundary walls are substantially smooth.

15

16     2.     A waveguide as claimed in Claim 1, and further

17 including a buffer layer formed on the substrate and

18 wherein the lower cladding layer is formed on the

19 buffer layer.

20

21     3.     A waveguide as claimed in either preceding claim,

22 wherein the substrate comprises silicon and/or silica

23 and/or sapphire.

24

25     4.     A waveguide as claimed in Claim 3, wherein said

26 buffer layer includes a thermally oxidised layer of the

27 substrate.

28

29     5.     A waveguide as claimed in any preceding claim,

30 wherein the buffer layer comprises doped silica.

31

32     6.     A waveguide as claimed in any preceding claim,

33 wherein the thickness of the buffer layer is in the

34 range 0.2 $\mu$ m to 20 $\mu$ m.

35

36     7.     A waveguide as claimed in any preceding claim,

1 wherein the lower cladding layer comprises doped  
2 silica.

3

4 8. A waveguide as claimed in any preceding claim,  
5 wherein the lower cladding layer includes at least one  
6 Phosphorus oxide and/or at least one Boron oxide.

7

8 9. A waveguide as claimed in Claim 8, wherein the  
9 lower cladding layer includes at least one Phosphorus  
10 oxide and at least one Boron oxide and wherein the  
11 Phosphorus oxide to Boron oxide ratio is such that the  
12 lower cladding layer refractive index is substantially  
13 equal to the refractive index of the buffer layer.

14

15 10. A waveguide as claimed in any preceding claim,  
16 wherein the lower cladding layer includes doped silica,  
17 at least one Phosphorus oxide and at least one Boron  
18 oxide and wherein the silica:Phosphorus oxide:Boron  
19 oxide ratio is in the range of 75 to 95 wt% silica:1 to  
20 7 wt% Phosphorus oxide:4 to 18 wt% Boron oxide.

21

22 11. A waveguide as claimed in Claim 10, wherein the  
23 lower cladding layer has a silica:Phosphorus  
24 oxide:Boron oxide ratio in the range of 80 to 90 wt%  
25 silica:2.5 to 6 wt% Phosphorus oxide:7.5 to 14 wt%  
26 Boron oxide.

27

28 12. A waveguide as claimed in Claim 11, wherein the  
29 lower cladding layer has a silica; to Phosphorus oxide;  
30 to Boron oxide ratio of 82 wt% silica; to 5 wt%  
31 Phosphorus oxide; to 13 wt% Boron oxide.

32

33 13. A waveguide as claimed in any preceding claim,  
34 wherein the thickness of the lower cladding layer is  
35 1 $\mu$ m to 20 $\mu$ m.

36

- 1 14. A waveguide as claimed in any preceding claim,  
2 wherein the waveguide core comprises doped silica.  
3
- 4 15. A waveguide as claimed in any preceding claim,  
5 wherein said mobile dopant ions of the waveguide core  
6 include Phosphorus and/or Fluorine and/or compounds of  
7 these elements.  
8
- 9 16. A waveguide as claimed in any preceding claim,  
10 wherein dopant ions of the waveguide core include  
11 Phosphorus and/or Fluorine and/or Aluminium and/or  
12 Boron and/or Germanium and/or Tin and/or Titanium  
13 and/or compounds of these elements.  
14
- 15 17. A waveguide as claimed in any preceding claim,  
16 wherein the waveguide core includes Phosphorus oxide  
17 and/or Boron oxide.  
18
- 19 18. A waveguide as claimed in Claim 17, wherein the  
20 waveguide core comprises  $P_2O_5$ - $SiO_2$ .  
21
- 22 19. A waveguide as claimed in any preceding claim,  
23 wherein the refractive index of the waveguide core  
24 differs from that of the lower cladding layer by at  
25 least 0.05%.  
26
- 27 20. A waveguide as claimed in any preceding claim,  
28 wherein the waveguide core includes silica, and at  
29 least one Phosphorus oxide and wherein the silica to  
30 Phosphorus oxide ratio is in the range of 75 to 95 wt%  
31 silica to 5 to 25 wt% Phosphorus oxide.  
32
- 33 21. A waveguide as claimed in Claim 20, wherein the  
34 waveguide core has a silica to Phosphorus oxide ratio  
35 of 80 wt% silica to 20 wt% Phosphorus oxide.  
36

1 22. A waveguide as claimed in any preceding claim,  
2 wherein the thickness of the waveguide core is in the  
3 range  $2\mu\text{m}$  to  $60\mu\text{m}$ .  
4

5 23. A waveguide as claimed in Claim 22, wherein the  
6 thickness of the waveguide core is  $6\mu\text{m}$ .  
7

8 24. A waveguide as claimed in any preceding claim,  
9 wherein the lower cladding layer and the upper cladding  
10 layer refractive indices are substantially equal.  
11

12 25. A waveguide as claimed in any preceding claim,  
13 wherein the lower cladding layer and the upper cladding  
14 layer comprise the same material.  
15

16 26. A waveguide as claimed in any preceding claim,  
17 wherein the waveguide core has a mobile ion dopant  
18 concentration higher than the mobile ion dopant  
19 concentration of the lower cladding layer or the upper  
20 cladding layer.  
21

22 27. A waveguide as claimed in any preceding claim,  
23 wherein the ion diffusion region is isotropic with  
24 respect to the waveguide core.  
25

26 28. A waveguide as claimed in any preceding claim,  
27 wherein the ion diffusion region surrounding the  
28 waveguide core forms a substantially rounded waveguide  
29 core.  
30

31 29. A waveguide as claimed in Claim 26 wherein the  
32 rounded waveguide core is elliptical or circular in  
33 cross-section.  
34  
35  
36

1 30. A method of fabricating a waveguide comprising the  
2 steps of:

3 providing a substrate;  
4 forming a doped lower cladding layer;  
5 forming a doped core layer on the lower cladding  
6 layer;  
7 forming a waveguide core from the core layer;  
8 forming a doped upper cladding layer to embed the  
9 waveguide core;

10 wherein mobile ion dopants included in the core  
11 layer undergo diffusion into the surrounding upper  
12 cladding layer and lower cladding layer to form an ion  
13 diffusion region around the waveguide core such that  
14 the waveguide core boundary walls are substantially  
15 smooth.

16  
17 31. A method as claimed in Claim 30, and including the  
18 step of forming a buffer layer on the substrate.

19  
20 32. A method as claimed in Claim 31, wherein the lower  
21 cladding layer is formed on said buffer layer.

22  
23 33. A method as claimed in any of Claims 30 to 32,  
24 wherein the steps of forming each of the lower cladding  
25 layer, the core layer and the upper cladding layer  
26 comprise the steps of:

27 depositing each layer; and  
28 at least partially consolidating each layer.

29  
30 34. A method as claimed in Claim 33, wherein any of  
31 the lower cladding layer, the core layer and the upper  
32 cladding layer partially consolidated after deposition  
33 is fully consolidated with the full consolidation of  
34 any other of the lower cladding layer, the core layer  
35 or the upper cladding layer.

36

- 1     35. A method as claimed in any of Claims 30 to 34,  
2     wherein the diffusion of mobile ion dopants in the core  
3     layer occurs during the consolidation of the lower  
4     cladding layer and/or the upper cladding layer.  
5
- 6     36. A method as claimed in any of Claims 30 to 35  
7     further comprising at least one thermal processing step  
8     after the formation of the upper cladding layer,  
9     wherein during said thermal processing of the waveguide  
10    the mobile ion dopants in the core layer undergo  
11    diffusion into the surrounding layers.  
12
- 13    37. A method as claimed in any of Claims 30 to 36,  
14    wherein the substrate comprises silicon and/or silica  
15    and/or sapphire.  
16
- 17    38. A method as claimed in any of Claims 30 to 37,  
18    wherein the buffer layer includes a thermally oxidised  
19    layer of the substrate.  
20
- 21    39. A method as claimed in any of Claims 30 to 38,  
22    wherein the buffer layer comprises doped silica.  
23
- 24    40. A method as claimed in any of Claims 30 to 39,  
25    wherein the thickness of the buffer layer formed is in  
26    the range of 0.2 $\mu$ m to 20 $\mu$ m.  
27
- 28    41. A method as claimed in any preceding claim,  
29    wherein the lower cladding layer comprises doped  
30    silica.  
31
- 32    42. A method as claimed in any preceding claim,  
33    wherein the lower cladding layer includes at least one  
34    Phosphorus oxide and/or Boron oxide.  
35
- 36    43. A method as claimed in Claim 42, wherein the lower

1 cladding layer includes at least one Phosphorus oxide  
2 and at least one Boron oxide and wherein the Phosphorus  
3 oxide to Boron oxide ratio is such that the lower  
4 cladding layer refractive index is substantially equal  
5 to the refractive index of the buffer layer.

6  
7 44. A method as claimed in any of Claims 30 to 43,  
8 wherein the lower cladding layer includes silica, at  
9 least one Phosphorus oxide and at least one Boron oxide  
10 and wherein the silica; to Phosphorus oxide; to Boron  
11 oxide ratio in the range of 75 to 95 wt% silica; to 1  
12 to 7 wt% Phosphorus oxide; to 4 to 18 wt% Boron oxide.

13  
14 45. A method as claimed in Claim 44, wherein the lower  
15 cladding layer has a silica; to Phosphorus oxide; to  
16 Boron oxide ratio in the range of 80 to 90 wt% silica;  
17 to 2.5 to 6 wt% Phosphorus oxide; to 7.5 to 14 wt%  
18 Boron oxide.

19  
20 46. A method as claimed in Claim 45, wherein the lower  
21 cladding layer has a silica; to Phosphorus oxide; to  
22 Boron oxide ratio of 82 wt% silica; to 5 wt% Phosphorus  
23 oxide; to 13 wt% Boron oxide.

24  
25 47. A method as claimed in any of Claims 30 to 46,  
26 wherein the thickness of the lower cladding layer is  
27  $1\mu\text{m}$  to  $20\mu\text{m}$ .

28  
29 48. A method as claimed in any of Claims 30 to 47,  
30 wherein the core layer comprises doped silica.

31  
32 49. A method as claimed in any of Claims 30 to 48,  
33 wherein said mobile dopant ions of the waveguide core  
34 include Phosphorus and/or Fluorine and/or compounds of  
35 these elements.

36



- 1     50. A method as claimed in any of Claims 30 to 49,  
2     wherein dopant ions of the waveguide core include  
3     Phosphorus and/or Fluorine and/or Aluminium and/or  
4     Boron and/or Germanium and/or Tin and/or Titanium  
5     and/or compounds of these elements.  
6
- 7     51. A method as claimed in any of Claims 30 to 50,  
8     wherein the core layer includes Phosphorus oxide and/or  
9     Boron oxide.  
10
- 11    52. A method as claimed in Claim 51, wherein the core  
12    layer comprises  $P_2O_5$ - $SiO_2$ .  
13
- 14    53. A method as claimed in any of Claims 30 to 52,  
15    wherein the refractive index of the waveguide core  
16    differs from that of the lower cladding layer by at  
17    least 0.05%.  
18
- 19    54. A method as claimed in any of Claims 30 to 53,  
20    wherein the waveguide core includes silica and at least  
21    one Phosphorus oxide and wherein the silica to  
22    Phosphorus oxide ratio is in the range of 75 to 95 wt%  
23    silica to 5 to 25 wt% Phosphorus oxide.  
24
- 25    55. A method as claimed in Claim 54, wherein the  
26    waveguide core has a silica to Phosphorus oxide ratio  
27    of 80 wt% silica to 20 wt% Phosphorus oxide.  
28
- 29    56. A method as claimed in any of Claims 30 to 55,  
30    wherein the thickness of the waveguide core is in the  
31    range  $2\mu m$  to  $60\mu m$ .  
32
- 33    57. A method as claimed in Claim 56, wherein the  
34    thickness of the waveguide core is  $6\mu m$ .  
35
- 36    58. A method as claimed in any of claims 31 to 57,

1 wherein said lower cladding layer and said buffer layer  
2 are formed substantially in the same step.

3

4 59. A method as claimed in any of claims 33 to 58,  
5 wherein the consolidation of the lower cladding layer  
6 is at a temperature or temperatures in the range 950°C  
7 to 1400°C.

8

9 60. A method as claimed in Claim 59, wherein the  
10 consolidation of the lower cladding layer is at a  
11 temperature or temperatures in the range 1100°C to  
12 1350°C.

13

14 61. A method as claimed in any of Claims 33 to 60,  
15 wherein the consolidation of the core layer is at a  
16 temperature or temperatures in the range 950°C to  
17 1400°C.

18

19 62. A method as claimed in Claim 61, wherein the  
20 consolidation of the core layer is at a temperature or  
21 temperatures in the range 1100°C to 1385°C.

22

23 63. A method as claimed in any of Claims 33 to 62,  
24 wherein the consolidation of the upper cladding layer  
25 is at a temperature or temperatures in the range 950°C  
26 to 1400°C.

27

28 64. A method as claimed in Claim 63, wherein the  
29 consolidation of the upper cladding layer is at a  
30 temperature or temperatures in the range 1100°C to  
31 1350°C.

32

33 65. A method as claimed in any of Claims 33 to 64,  
34 wherein the temperature or temperature range at which  
35 the lower cladding layer is consolidated is greater  
36 than the temperature or temperature range at which the

1 core is consolidated.  
2

3 66. A method as claimed in any of Claims 33 to 65,  
4 wherein the temperature or temperature range at which  
5 the upper cladding layer is consolidated is  
6 substantially equal to the temperature or temperature  
7 range at which the core layer is consolidated.  
8

9 67. A method as claimed in any of Claims 33 to 67,  
10 wherein at least one of the lower cladding layer, the  
11 core layer, and the upper cladding layer is deposited  
12 by a Flame Hydrolysis Deposition process and/or  
13 Chemical Vapour Deposition process.  
14

15 68. A method as claimed in Claim 67, wherein the  
16 Chemical Vapour Deposition process is a Low Pressure  
17 Chemical Vapour Deposition process or a Plasma Enhanced  
18 Chemical Vapour Deposition process.  
19

20 69. A method as claimed in any of Claims 33 to 68,  
21 wherein the consolidation is by fusing using a Flame  
22 Hydrolysis Deposition burner.  
23

24 70. A method as claimed in any of Claims 33 to 68,  
25 wherein the consolidation is by fusing in a furnace.  
26

27 71. A method as claimed in either of Claims 69 or 70,  
28 wherein the step of fusing the lower cladding layer and  
29 the step of fusing the core layer are performed  
30 simultaneously.  
31

32 72. A method as claimed in any of Claims 30 to 71,  
33 wherein the waveguide core formed from the core layer  
34 is square or rectangular in cross-section.  
35

36 73. A method as claimed in any of Claims 30 to 72,

1 wherein the waveguide core is formed from the core  
2 layer using a dry etching technique and/or a  
3 photolithographic technique and/or a mechanical sawing  
4 process.

5  
6 74. A method as claimed in Claim 73, wherein the dry  
7 etching technique comprises a reactive ion etching  
8 process and/or a plasma etching process and/or an ion  
9 milling process.

10  
11 75. A method as claimed in any of Claims 30 to 74,  
12 wherein the diffusion of the said mobile dopant ions  
13 from the waveguide core is isotropic.

14  
15 76. A method as claimed in any of Claims 30 to 75,  
16 wherein the diffusion of the said mobile dopant ions  
17 from the waveguide core swells the boundary walls of  
18 the waveguide core.

19  
20 77. A method as claimed in Claim 76, wherein the  
21 diffusion of the said mobile dopant ions swells the  
22 boundary walls of the waveguide core to form a  
23 substantially rounded waveguide core.

24  
25 78. A method as claimed in Claim 77, wherein the  
26 rounded waveguide core is elliptical or circular in  
27 cross-section.

28  
29 79. A waveguide substantially as described herein and  
30 with reference to Figs. 2A to 2E of the accompanying  
31 drawings.

32  
33 80. A method of fabricating a waveguide substantially  
34 as described herein and with reference to Figs. 2A to  
35 2E of the accompanying drawings.

36